AD 677472

UNDERWATER SYSTEMS, INC.

TECHNICAL PROGRESS REPORT NO. 20

IITRI 10 TON 1968 SHOT SERIES

Prepared by:

Richard J. Hecht
Daniel D. Woolston
Marvin S. Weinstein

Sponsored by:

ADVANCED RESEARCH PROJECTS AGENCY (ARPA)
OFFICE OF NAVAL RESEARCH (ONR)

Contract No. NOnr 4026(00)
Project Code No. 3810
ARPA Order No. 218
ONR Research Project: RR-004-08-01

15 July 1968

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INTRODUCTION

Under separate Prime Contract (DA-49-082-OSA-3198) IITRI has undertaken a program for development of large charges for use at sea as seismic sources. The program includes the development of slurry type explosives and appropriate containers. The first at-sea tests of 10 ton shots were performed off the coast of Southern California on February 14 and 21, 1968. The explosive bodies were launched from a ship, with delayed sinking to permit the vessel to reach a safe stand-off distance. The purpose of these tests was to obtain design information for use in the development of charges in the fractional kiloton range. Underwater Systems, Inc., under Prime Contract NOnr 4026(00), furnished instrumentation and manpower to monitor a number of parameters. These include:

(1) Yield

(2) Detonation depth

(3) Terminal velocity of vehicle

(4) Detonation time

(5) Vehicle attitude

The results obtained are discussed in the body of this report and are summarized in Table I. Details of the measurement procedure are given in Appendices A and B.

Table I - Summary of Results

Yield

Energy basis - 12 to 13 tons TNT equivalent

Bubble Pulse Period basis - 21 tons TNT equivalent

	Shot 1	Shot 2
Detonation Depth (ft)	1,825	3,025
Terminal Velocity (ft/sec)	18.9	18.8
Detonation Time (GMT)	16 Feb 1968 18:01:52.99 ±.01	21 Feb 1968 23:32:08.35 ±.01
Vehicle Attitude	Essentially vertical	Essentially vertical

RESULTS

1. TNT Equivalence.

The yield of the explosive under test is based on a comparison with TNT. The standard shock wave and bubble pulse equations given by Weston, Reference (1), are used. A number of different measures of equivalence are available, depending upon the portion of the pressure time history which is used for the computation. Figure (1) shows the shock wave for shot No. 2. Figure (2) shows the shock wave and bubble pulses.

1.1 Peak Amplitude of the Shock Wave. The peak amplitude of the shock wave provides a significant measure of TNT equivalence. The peak level is given by:

$$P_o = 2.16 \times 10^4 \left(\frac{W^{1/3}}{r}\right)^{1.13} \text{ psi} \qquad (1)$$

W = yield in pounds

r = range in feet

Since the peak amplitude of the shock wave is independent of detonation depth, the experimentally measured levels of the two detonations were plotted together in Figure (3). The smooth curves for 10 and 13 tons of TNT were computed from Equation (1).

The peak signal varies as the cube root of yield, and a large change in yield is required to produce a small change in level. For example, a 10% change in yield introduces a 3½% change in signal level. Since the shock wave duration is very short, some rounding of the peak occurs due to the limited system bandwidth of approximately zero to 2,000 Hertz. This tends to make the measured levels somewhat lower than the true levels. Additionally, system noise introduces some fluctuations which can either increase or decrease the measured levels. Both of these effects can be observed in Figure (1). The average value of the data points corresponds to a yield of about 11.5 tons TNT equivalent. If the one low reading for shot (2) at a range of 2,190 feet is discounted, an average yield of about 13 tons TNT equivalent is obtained. This is our best estimate for this measure of equivalence. A statistical analysis is unwarranted since only a few data points are available.

For a TNT equivalence factor of 1.3, the constant 2.16 in Equation (1) becomes 2.38, for the actual weight of the slurry explosive used by IITRI.

1.2 Time Constant of the Shock Wave. A second measure of the TNT equivalence is the decay constant of the shock wave. The pressure time history of the shock wave is represented by:

$$p = P_o e^{-t/T_o} \qquad (2)$$

where: T_o is the decay constant, and for TNT is given by:

$$T_o = 58\ W^{1/3}\ (W^{1/3}/r)^{-0.22}\ \mu\text{secs} \qquad (3)$$

The time constant is also insensitive to yield. A 10% change in yield corresponds to a 2½% change in the time constant. The exponential representation of the signal is approximate and holds to only one or two time constants. This measure is therefor primarily useful for validating the TNT equivalence determined from the peak amplitude measurement. By fitting the theoretical decay curve to the observed signal, significant errors in peak level due to rounding and/or noise can be determined, and a correction applied. This is illustrated by Figures (4) and (5). The solid curves are tracings of the average experimental signal with noise effects removed by eye averaging. The dashed curves are based on Equations (2) and (3) for a 13 ton TNT equivalent yield, with the level adjusted for best fit to the experimental data at $t = T_o$, and are shown only when they depart from the experimental data. The experimental peak level is significantly lower than the empirical level for the data of Figure (4), and substantially the same for the data of Figure (5). Significant corrections were found for the two data points of Figure (3) which showed the largest deviation from the theoretical predictions, as indicated by the arrow heads. While the absolute value of these corrections are dependent upon the subjective process of curve fitting, it is clear that in both cases the deviation from the theoretical prediction is reduced. We therefore conclude that this measurement of TNT equivalence supports the conclusions reached from the peak signal level.

1.3 <u>Bubble Pulse Period</u>. The first bubble pulse period is also a useful measure of TNT equivalence. When explosives are compared to TNT it is usually found that this measure gives different results than that obtained from the shock wave parameters. The shock wave equivalence determines the total available radiated energy at the high frequencies, and a portion of the energy at the low frequencies. The bubble pulse period determines the spectral interference pattern between the shock wave and bubble pulse. A high TNT equivalence lowers the frequency at which the first spectral maximum occurs, increasing effectiveness as a seismic source.

The bubble pulse period for TNT is given by:

$$\tau = 4.36\ W^{1/3} d_o^{-5/6} \qquad (4)$$

where: d_o is the detonation depth plus 32 feet

For the first detonation the measured bubble pulse period was .287 secs, and the detonation depth was 1,825 feet. For the second detonation the comparable figures were .188 secs and 3,025 feet. From Equation (4) this yields a TNT equivalence of 21 tons for both shots.

For a TNT yield equivalence factor of 2.1, the constant 4.36 in Equation (4) becomes 5.59, when the actual weight of the slurry explosive is used for computation.

1.4 Bubble Pulse Parameters. Additional measures of TNT equivalence are the peak amplitude and decay constant of the first bubble pulse. The pressure time history is represented by an increasing exponential followed by a decreasing exponential, with identical time constants. These formulae are less exact than those used for the shock wave. In particular, the predicted cusp is rarely observed, and the time constants for each side of the signal are usually somewhat different. Equivalence calculations are therefore less reliable. Of perhaps greater interest is the energy density at the low frequencies. This can be computed more accurately by extrapolating the bubble pulse peak to form an exponential cusp prior to reading the experimental peak value and time constant. When this is done we obtain a TNT equivalent of 11 tons based on peak signal, and 13 tons based on the time constant. The governing equations are:

$$P_1 = 3,450 \; (W^{1/3} /r) \quad \text{psi} \tag{5}$$

$$T_1 = 1.39 \; W$$

1.5 Energy. The effectiveness of the explosive as a seismic source is determined by the energy density at low frequencies. For the shock wave and first bubble pulse, this is given by:

$$E_o = \frac{2P_o^{\,2} \, T_o^{\,2}}{\rho c} \tag{7}$$

$$E_1 = \frac{8P_1^{\,2} T_1^{\,2}}{\rho c} \tag{8}$$

From the TNT equivalence determination made for P_o, T_o, P_1, and T_1 we obtain about 13 tons TNT equivalent for the shock wave and 12 tons for the bubble pulse. We therefore conclude that the slurry explosive used provides 20% to 30% more energy than TNT. In addition, the increase in the bubble pulse period corresponding to an equivalent 110% increase in yield, decreases the frequency for the first spectral maximum. As a result, the effective energy available for seismic detection at long range can be considerably greater than that for an equal weight of TNT, depending on the detonation depth.

2.0 Dynamic Characteristics. Data on sink rate, detonation time and angle to the vertical were determined from data obtained with the acoustic-radio telemetry system.

2.1 Sinking Rate and Detonation Depth. Figures (6) and (7) show the depth vs. time for the 1st and 2nd shots, respectively.

Shot 1.

Detonation depth - 1,825 ft.

Terminal velocity - 18.9 ft/sec

Shot 2.

Detonation depth - 3,025 ft.

Terminal velocity - 18.8 ft/sec

During the time periods when no data is shown, the telemetry signal was not received. Possible causes of this phenomena are discussed in Appendix C. It is concluded that the probable cause was air bubble screening due to venting around the pinger body after the rupture diaphragm burst during descent.

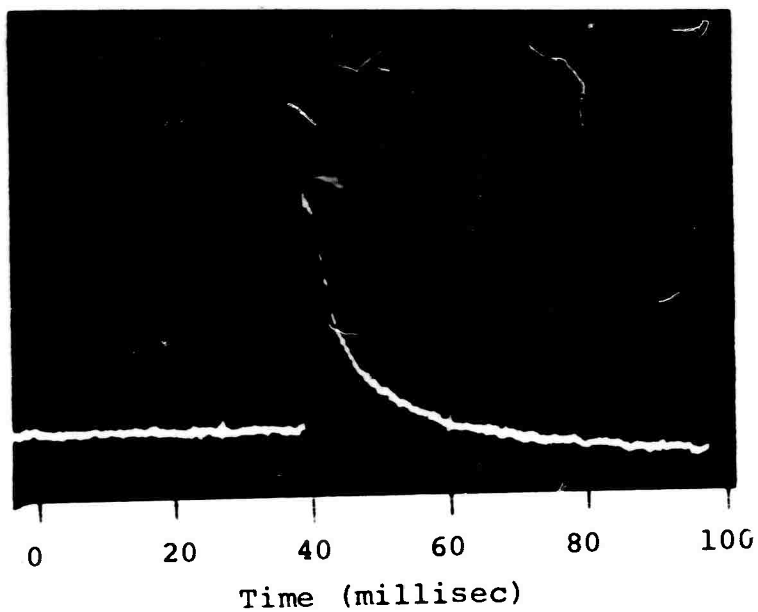


Figure (1)

Shock wave, shot 2, short range 2,200 ft.

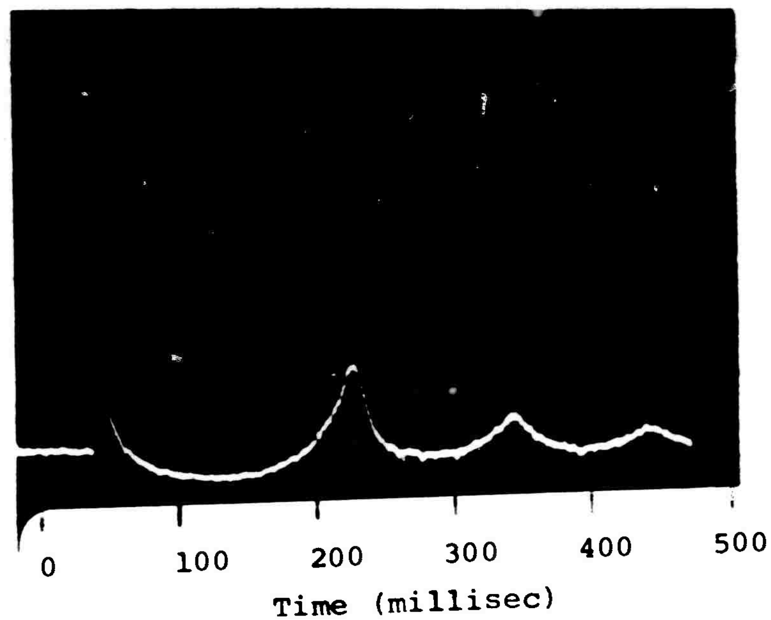


Figure (2)

Shock wave and first three bubble pulses for shot 2. The negative going signal at about 475 millisecs is the surface reflection of the shock wave.

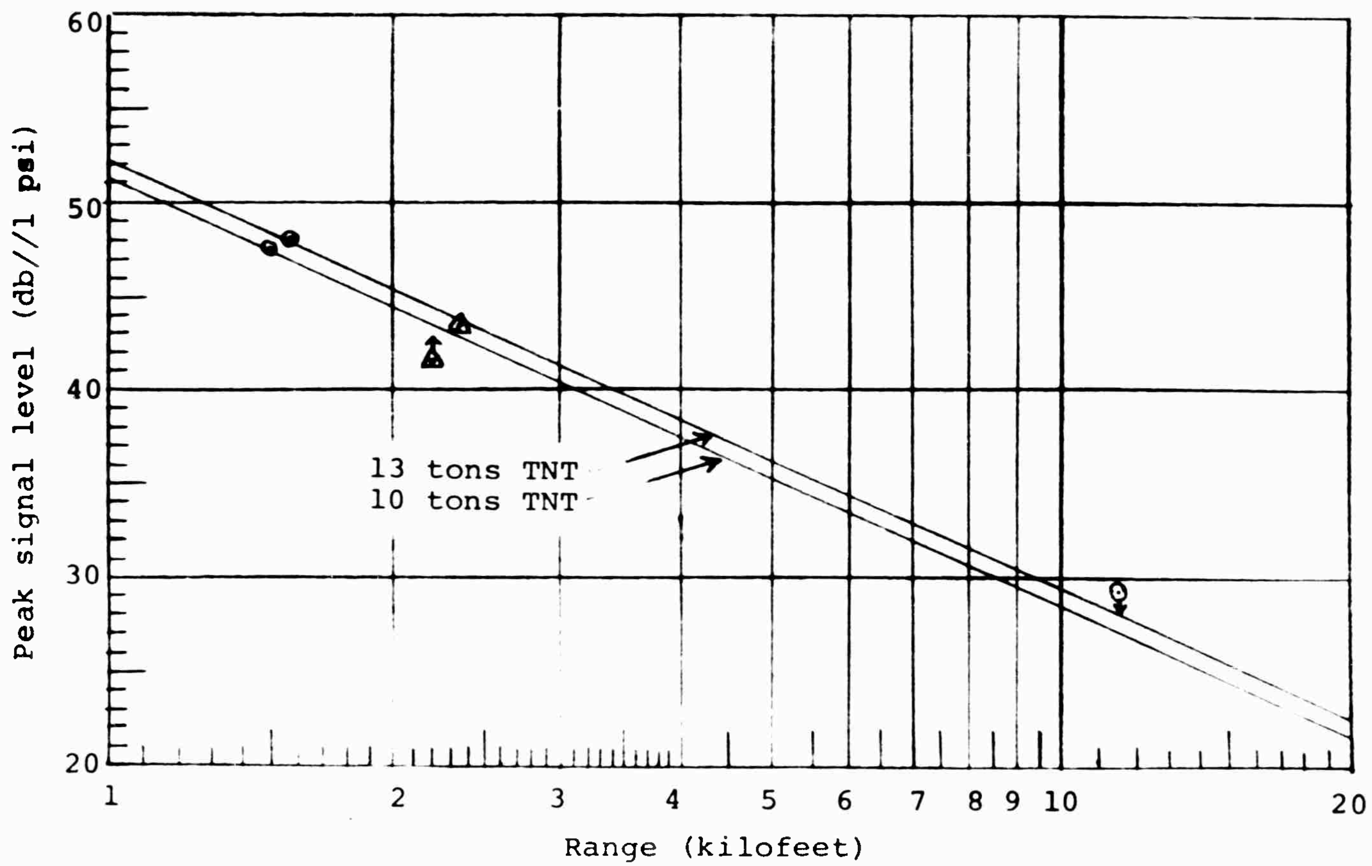


Figure (3)

Peak shock wave level as a function of range

o Shot 1
Δ Shot 2
↑ Corrections for round off and noise

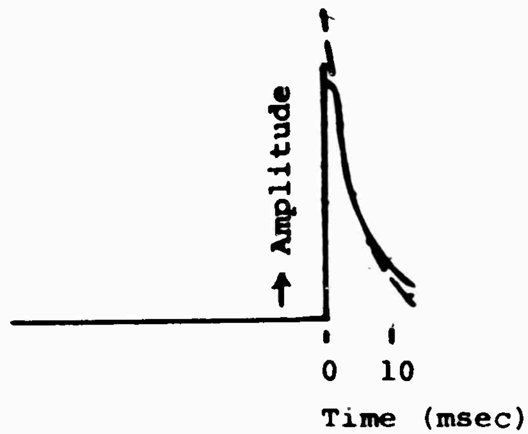


Figure (4)

Shock wave time constant reconstruction. Shot No. 2 at 2,190 ft. Time constant, 4.4 msecs. Corrected increase in signal level, 1.5 db.

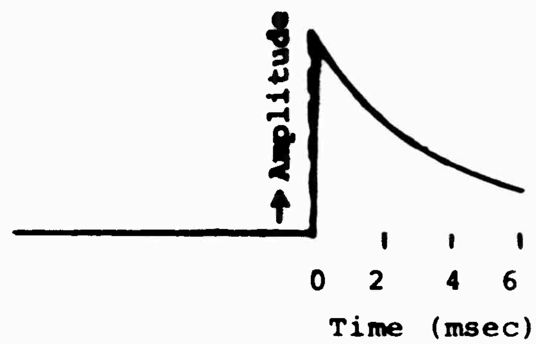


Figure (5)

Shock wave time constant reconstruction. Shot No. 1 at 1,490 ft. Time constant, 4.1 msecs. Negligible correction of signal level.

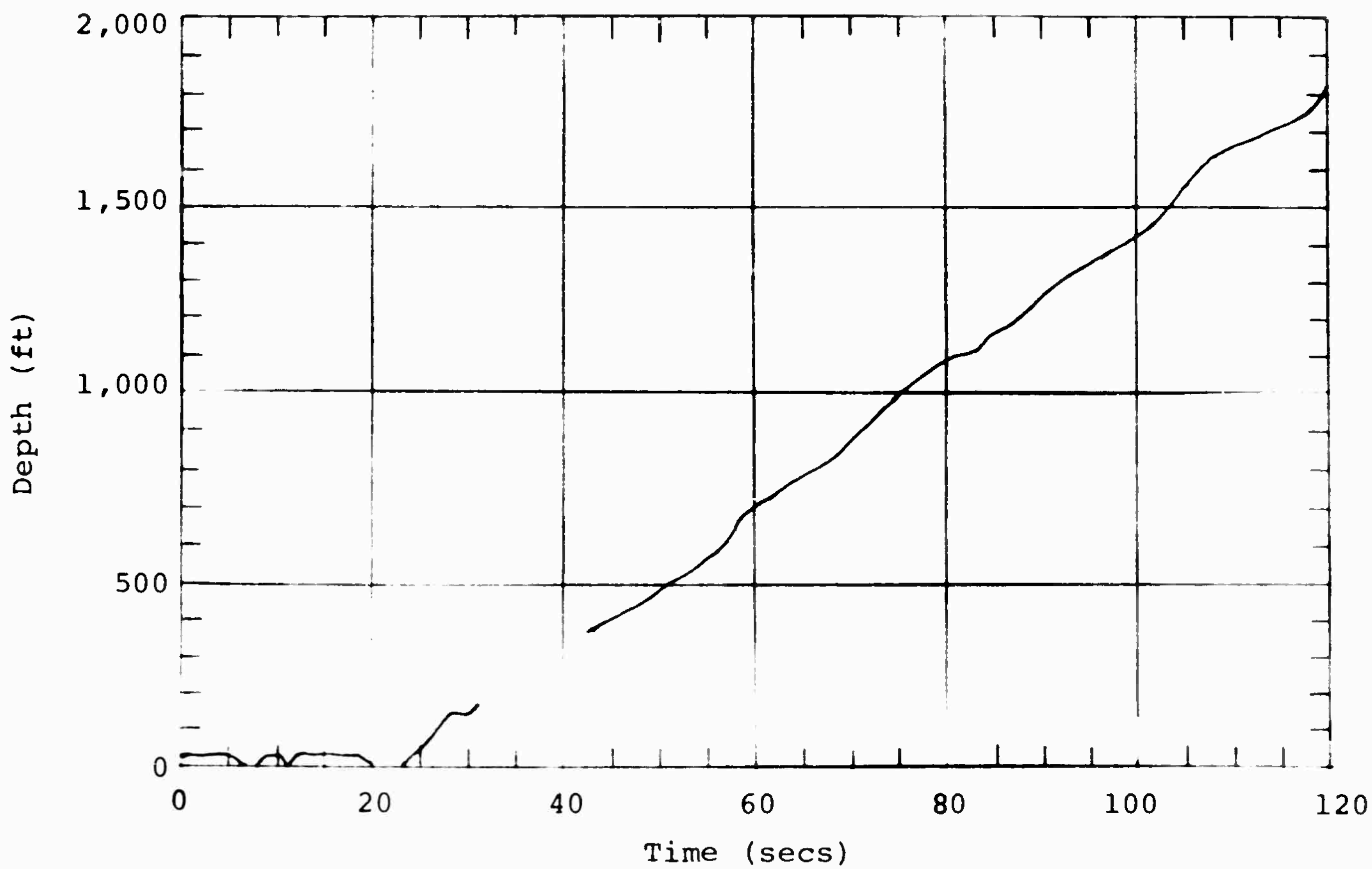


Figure (6)

Sinking depth vs time for the first vehicle. Detonation depth 1,825 ft. Terminal velocity 18.9 ft/sec. See Appendix C for data gaps.

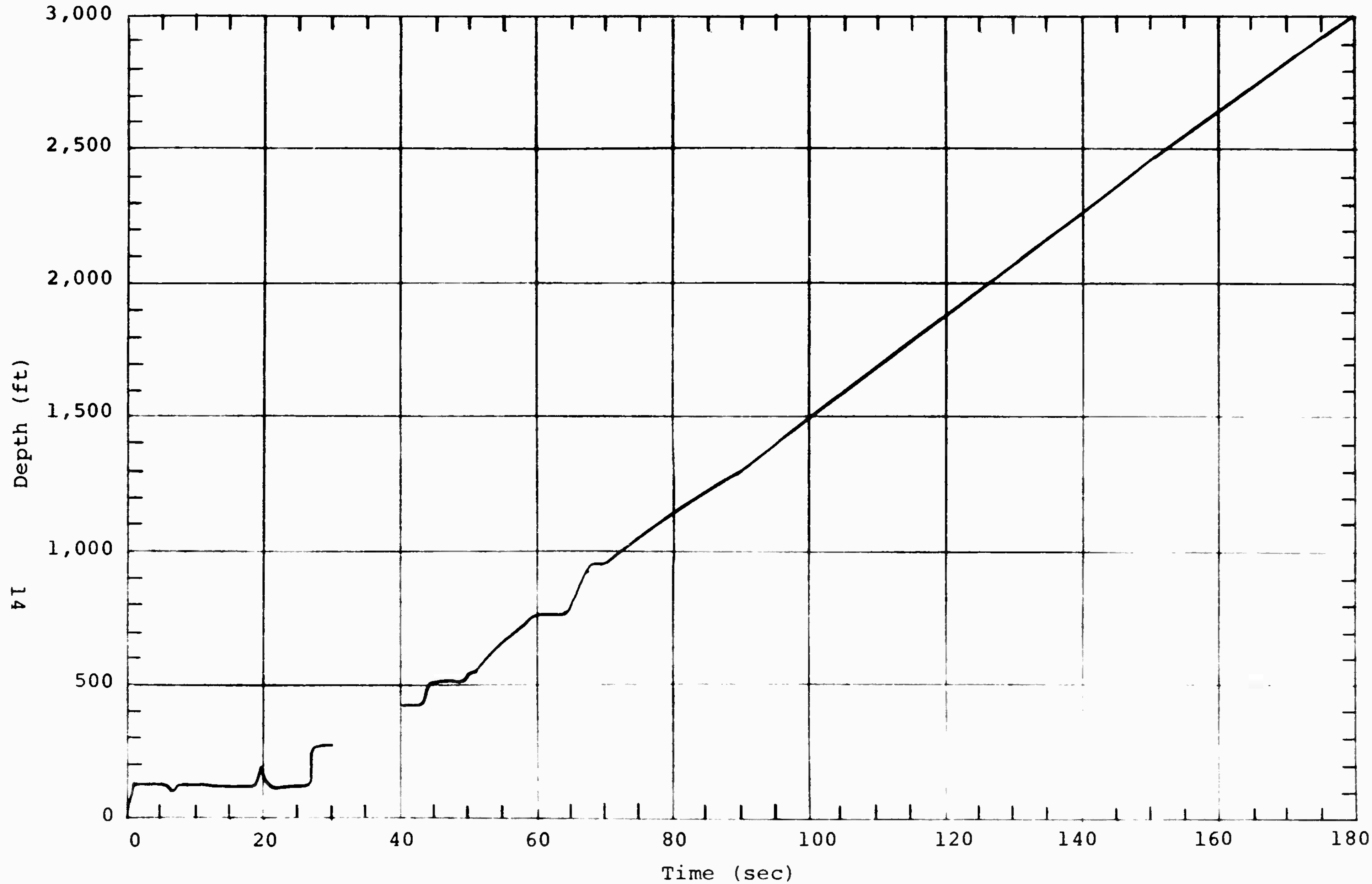


Figure (7)

Sinking depth vs. time for the second vehicle. Detonation Depth 3,025 ft. Terminal velocity 18.8 ft/sec. See Appendix C for data gaps.

APPENDIX A
DATA GATHERING SYSTEM

Figure A-1 shows the general arrangement of buoys, pingers, and recording vessel during the operation at sea. Three data acquisition systems were used as described below. The acoustic-radio telemetry link was the primary system.

1. Acoustic-Radio Telemetry

An acoustic pinger was attached to the explosive vehicle. Each of two buoys received the pinger signal on a hydrophone and relayed the data by radio telemetry to the receiving ship.

2. Hard Wire - Radio Telemetry

A buoy connected by torpedo wire to the pinger data encoding circuits provided a hard wire link, bypassing the acoustic telemetry. The data is relayed to the recording vessel by radio telemetry.

3. Shipboard System

Hydrophones and shock wave gages were used over the side at the recording vessel for additional back up.

Acoustic-Radio Telemetry

An acoustic pinger operating at 4.166 kilohertz was mounted on each of the explosive vehicles. The source level was approximately 75 db re one microbar at one yard. The output consisted of a series of coded pulses.

a. An internal chronometer controlled the emission of 15 millisecond pulses at one second intervals.

b. In the zero to 1/2 second time interval following each of the timing pulses an 8 millisecond pulse controlled by an internal depth sensor was generated. The exact time delay is proportional to vehicle depth.

c. In the 1/2 to one second time interval following each of the timing pulses a second 8 millisecond pulse controlled by an internal yaw indicator was generated. The exact time delay is related to yaw, as discussed in Appendix B.

Each of the two acoustic-radio telemetry buoys contained a hydrophone at a depth of about 50 feet, and a deep tourmaline gage to monitor the explosive signal. The two buoys were launched prior to the vehicle launch. One buoy was tied off from the vehicle with 300 feet of line. A release mechanism was inserted in the line and is actuated when the vehicle sinks. The second buoy was tied off from the first with 200 feet of line.

The acoustic telemetry signal is relayed to the monitoring vessel for recording. The controlled pulse system permits a direct measurement of vehicle depth and attitude as a function of time. A typical data sequence is shown in Figure A-2.

Prior to sinking, the coded pulse sequence controlling the pinger is relayed to the recording vessel by radio telemetry from the wire-link buoy (see below). The output of a shipboard chronometer and WWV time signals are also recorded. Thus, the pinger time series can be related to absolute time. The shock wave resulting from the detonation overloads the hydrophone system, but the arrival time is determined. From the arrival time of the preceding timing pulse emitted by the pinger the acoustic travel time is known, and the detonation instant is determined. (See Appendix D for shock wave velocity correction). From the arrival time of the shock wave at the tourmaline gage the range to the gage is determined.

Hard Wire - Radio Telemetry

The hard wire radio telemetry buoy was mounted on and launched with the vehicle. Upon sinking the buoy is submerged to a shallow depth until the release mechanism actuates at which time the buoy pops to the surface. One reel of wire is attached to the buoy, and a second to the vehicle. As the vehicle sinks wire is payed out. The wire connects the radio telemetry in the buoy to the pulse control circuits in the pinger. Data on vehicle depth and yaw is relayed by radio telemetry, bypassing the acoustic link. The buoy does not have any provision for monitoring the explosive signal.

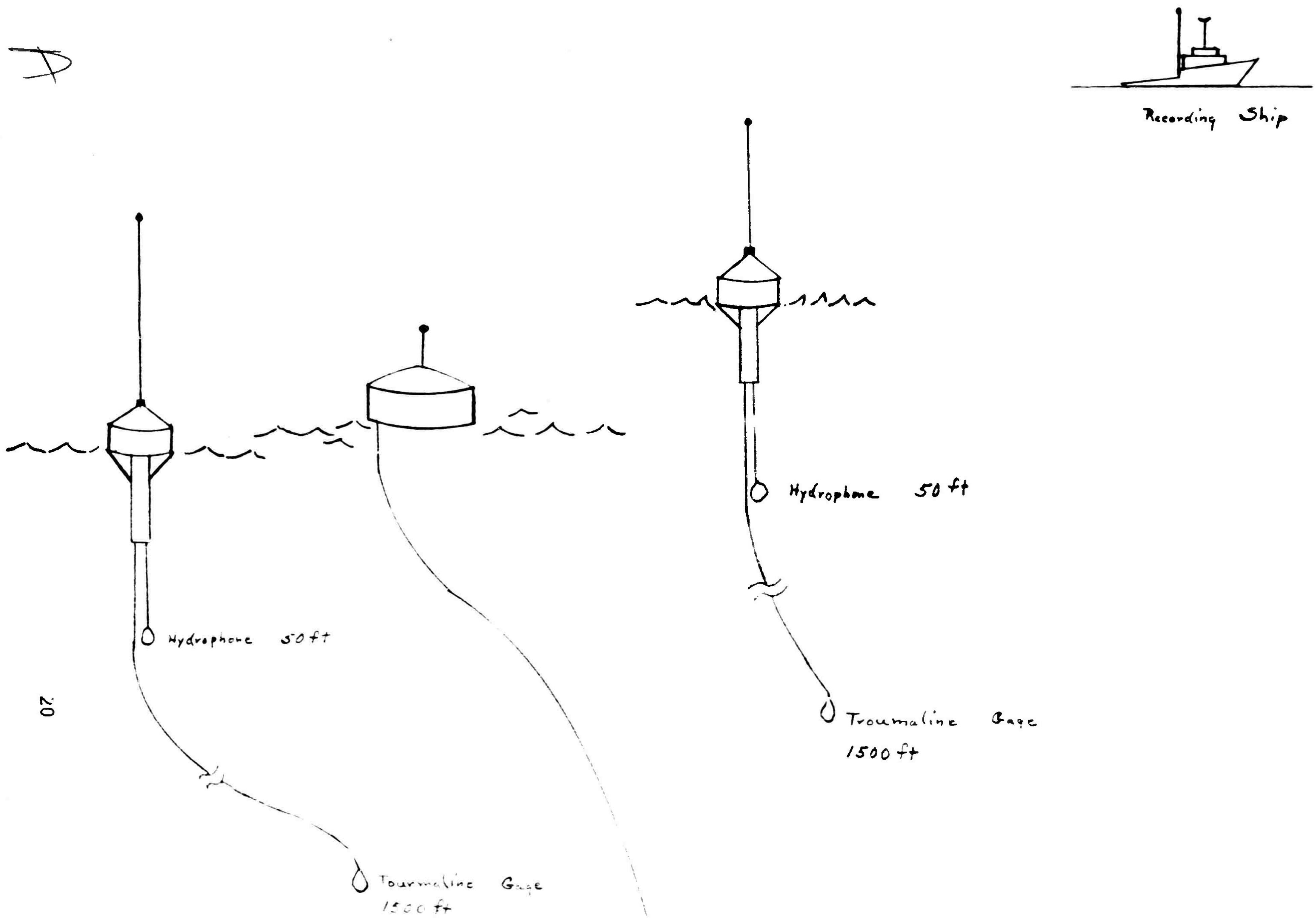
This buoy system operated properly in harbor trials. During the field operation, the release mechanism was actuated during launch of the first vehicle. The buoy rolled off and became inoperative. This malfunction was eliminated by modification to the release system between trials. In the second test the buoy behaved properly during launch and telemetered data up to the time the vehicle sank after which telemetry signal was lost. Examination of the buoy upon completion of the tests indicated that failure was due to water leakage at the antenna during submergence.

Shipboard System

An over-the-side hydrophone and two tourmaline gages for detecting the explosive signals were placed over the side. The primary purpose of this system is to obtain additional data on the pressure time history of the explosive signal. The peak level of the shock wave for shot (1), at a range of approximately 12,000 feet, shown in Figure (3), was obtained with the shipboard system.

Redundancy

As is apparent from the preceding discussion that a considerable amount of redundancy is built into these systems. This has been done in order to insure that satisfactory data is obtained despite failure of individual components or entire sub-systems. This redundancy is essential, since each test is a one shot operation.



Recording Ship
Hydrophone 50 ft
Troumaline Gage
1500 ft
Hydrophone 50 ft
Tourmaline Gage
1500 ft

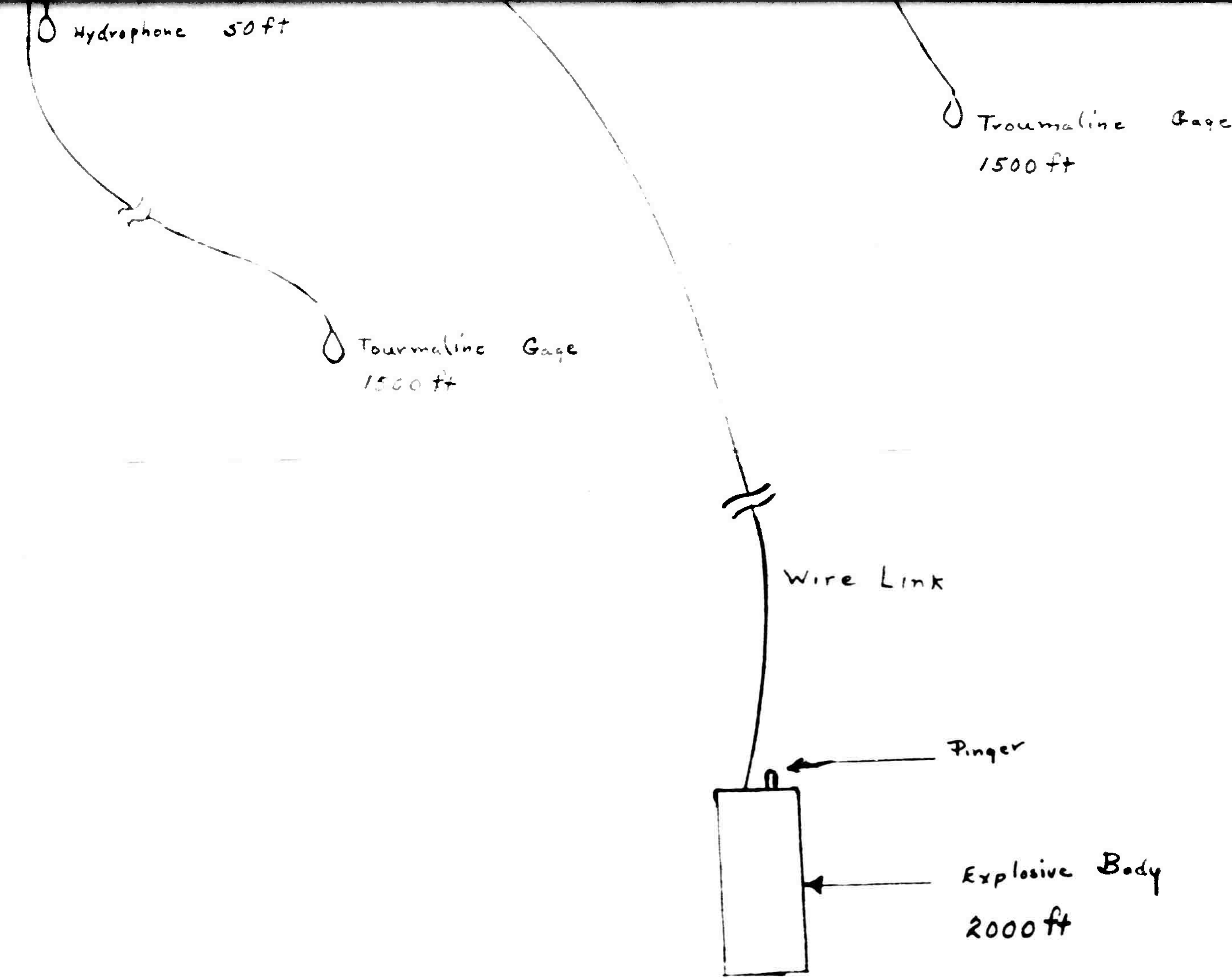


Figure A-1
System Configuration

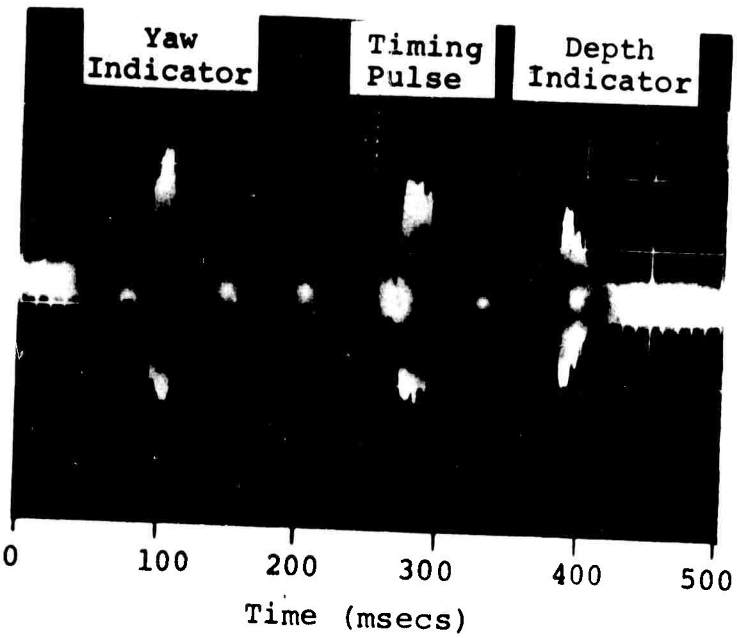


Figure A-2

Typical pulse time sequence as received and recorded after acoustic and radio telemetry. This was the last pulse sequence received from the first explosive vehicle prior to detonation.

APPENDIX B

YAW MEASUREMENTS

To measure gross yaw, a tilt indicator was provided by IITRI and placed in the pinger. The tilt indicator controlled the time delay between the timed one second acoustic pulses and the yaw indicator pulses. The time delay as a function of tilt angle is shown in Figure B-1. As can be noted, the linear portion of the curve lies between approximately 30° and 150°. Since IITRI was primarily interested in gross yaw the decreased sensitivity between 0° and 30° was acceptable. Figures B-2 and B-3 show the results obtained for the first and second vehicles respectively. In both cases the measured time delays indicate a near vertical attitude. The fluctuations indicate reading accuracy.

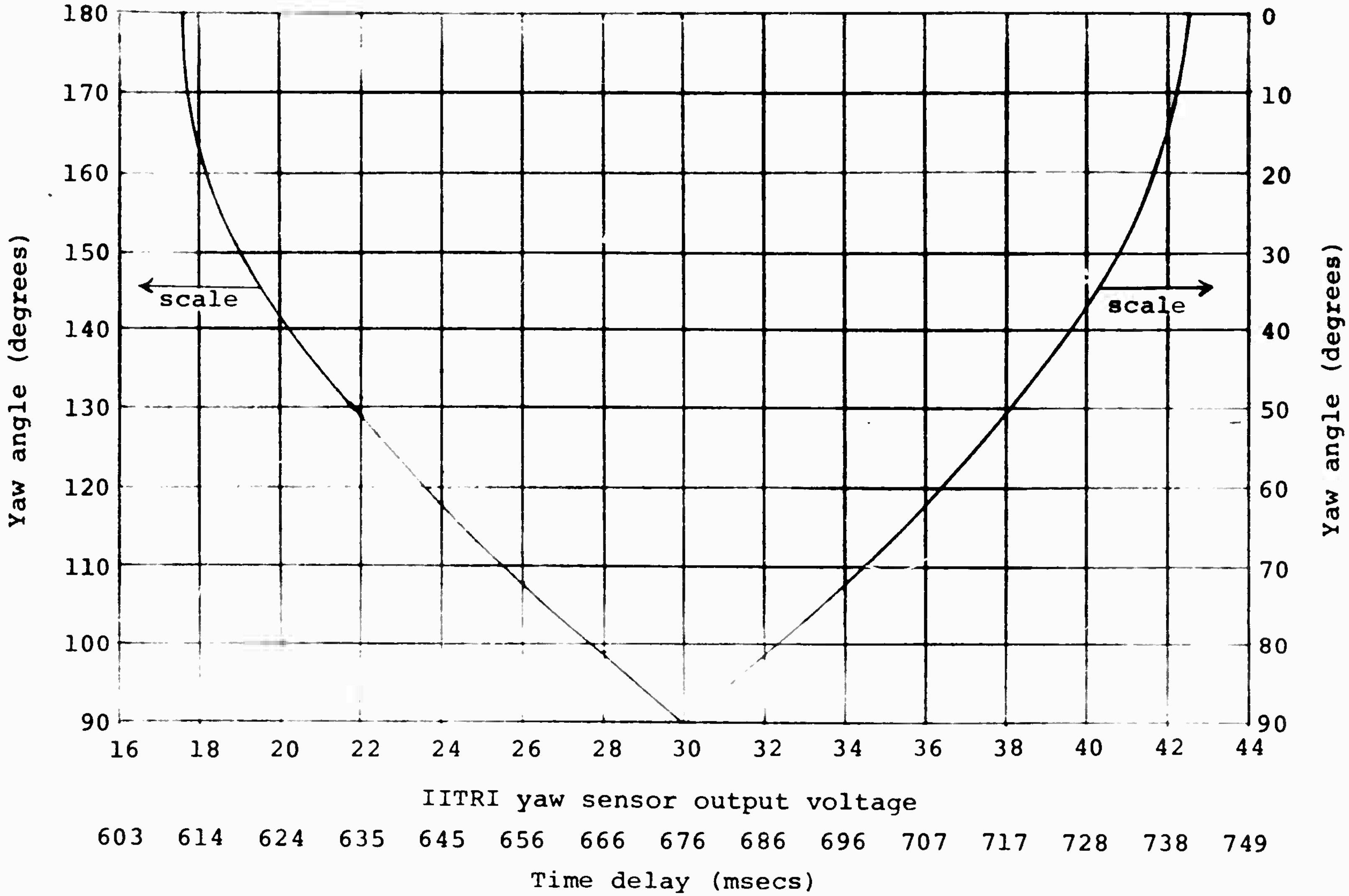


Figure B-1

Yaw angle vs. sensor output and time delay

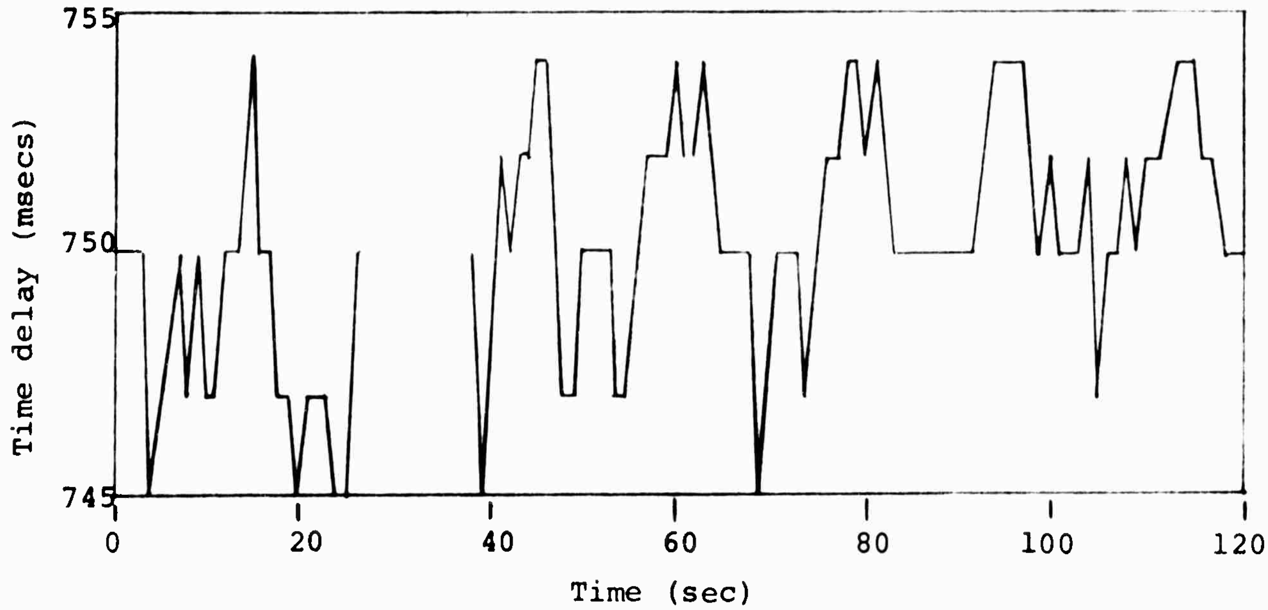


Figure B-2

Yaw time delay vs. sinking time, first vehicle.
Accuracy of readings ±5 ms plus static offset.

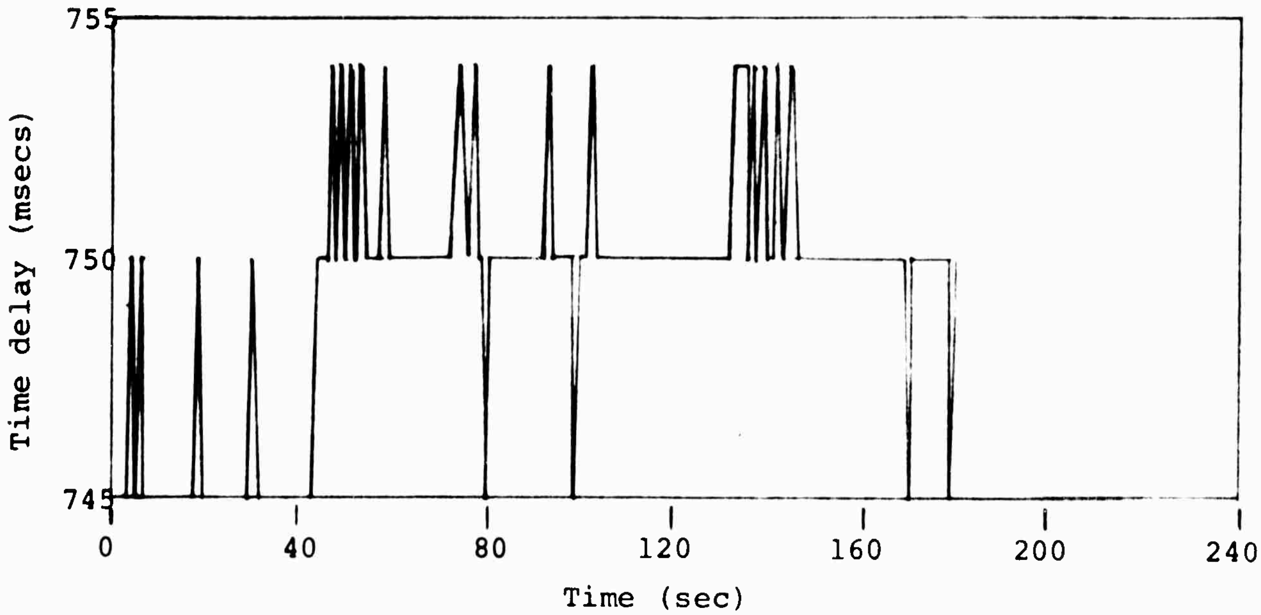


Figure B-3

Yaw time delay vs. sinking time, second vehicle.
Accuracy of readings ±5 ms plus static offset.

APPENDIX C
LOSS OF ACOUSTIC TELEMETRY SIGNAL

During the time period when data is not shown, telemetry signal was not received. The cause is not entirely understood. The several possibilities are discussed below.

1. Ray path calculations based on the sound velocity profile and the pinger-hydrophone configuration indicate that good signal should have been received. Acoustic shadowing due to refraction did not occur.

2. Interference due to direct and surface reflected signals would introduce ping-to-ping fluctuations. Since this was not observed, and the loss of signal occurred over the same vehicle depth range for both buoys and for both shots, surface phenomena have been discounted as a possible cause.

3. The acoustic pinger was mounted on the explosive vehicle as shown in Figure C-1. Computation of the reflected signals from the vehicle end plate indicates that interference between a direct signal and a vehicle reflected signal would not have caused loss of signal during the interval in which it occurred.

4. Acoustic shadowing by the vehicle could occur in the event of gross yaw. Since the test results indicate the absence of gross yaw this possibility has been discounted.

5. It is possible that loss of signal was due to air bubble screening of the pinger, but it is not possible to prove this conclusively. The pinger extends through the vehicle end plate into the buoyancy chamber. The pinger body was bolted to the end plate. The clearance space was filled with RTV rubber to prevent water entry through this space while the vehicle was on the surface. Since this was a simple mastic fill, without back-up rings, the RTV could be squeezed out by a pressure head. When the vehicle leaves the surface and sinks, the external water pressure will be greater than the internal pressure in the buoyancy chamber until the rupture diaphragm breaks. During this time interval water will enter the chamber through the vent holes, and if the pressure differential becomes sufficiently large, the RTV would be squeezed out. When the rupture diaphragm breaks, the rapid entry of water equalizes the pressure head, and the remaining air vents under gravity through the vent holes, and the clearance space around the pinger body. This would produce a cylindrical air bubble screen around the pinger head, greatly attenuating the radiated signal, until all air had vented. This possible cause is consistent with the observed loss of data on both hydrophones for the same range of water depths for both shots, but cannot be conclusively demonstrated.

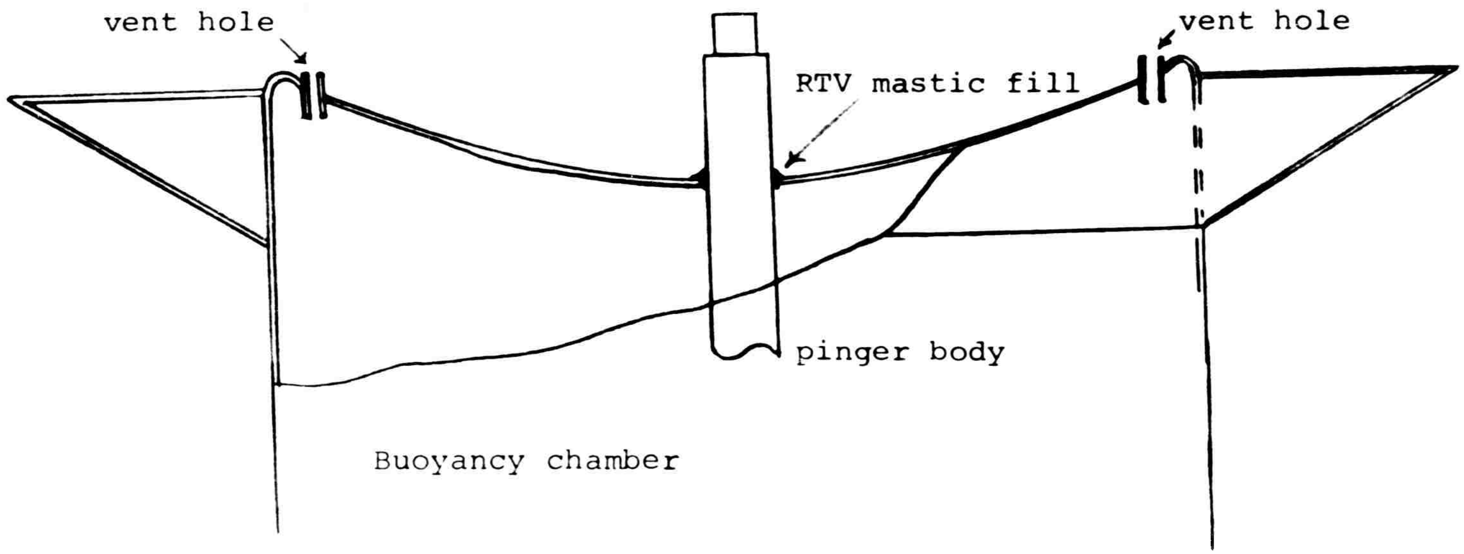


Figure C-1
Pinger installation on vehicle end plate.

APPENDIX D
SHOCK WAVE VELOCITY CORRECTION

All range and timing computations have been based on acoustic propagation velocities. Due to the high pressure associated with the shock wave it propagates at a higher velocity. The measured detonation time can be corrected for this second order effect.

For the slurry explosive used in these tests we have found that the peak pressure as a function of the actual weight of explosive used is given by:

$$P_o = 2.38 \times 10^4 \left(\frac{W^{1/3}}{r}\right)^{1.13} \qquad \text{D-1}$$

The propagation velocity increases at the rate of .04 ft/sec/psi for sea water. The propagation velocity of the shock wave is therefore given by:

$$\begin{aligned} c &= c_o + (.04)(2.38) \times 10^4 \left(\frac{W^{1/3}}{r}\right)^{1.13} \qquad \text{D-2} \\ &\; c_o + 954 \left(\frac{W^{1/3}}{r}\right)^{1.13} \end{aligned}$$

where: c_o is the acoustic velocity

The travel time to a range R, for propagation at the acoustic velocity is given by:

$$\int_{o}^{R} \frac{dr}{c_o} = \frac{R}{c_o} \qquad \text{D-3}$$

For the shock wave, we obtain:

$$t = \int_{o}^{R} \frac{dr}{c_o + 954\ (W^{1/3}/r)^{1.13}} \qquad \text{D-4}$$

If we let x equal the correction to the shock wave propagation time we obtain:

$$\int_{o}^{R} \frac{dr}{c_o} - x = \int_{o}^{R} \frac{dr}{c_o + 954\ (W^{1/3}/r)^{1.13}} \qquad \text{D-5}$$

and:

$$x = \frac{1}{c_o} \int_{o}^{R} \frac{954\ (W^{1/3}/r)^{1.13}}{c_o + 954\ (W^{1/3}/r)^{1.13}}\ dr \qquad \text{D-6}$$

Due to the exponent of 1.13 this cannot be easily integrated. If we replace the exponent 1.13 by unity we can easily determine an upper limit for the correction time x.

$$x < \frac{1}{c_o} \int_o^R \frac{954\ W^{1/3}}{c_o r + 954\ W^{1/3}} \qquad \text{D-7}$$

which yields:

$$x < \frac{954\ W^{1/3}}{c_o^{\ 2}} \left\{ \ln\left(R + \frac{954\ W^{1/3}}{c_o} \right) - \ln\left(\frac{954\ W^{1/3}}{c_o} \right) \right\} \qquad \text{D-8}$$

For 10 tons of slurry at a range of 2,000 feet, we obtain:

$$x < .009 \text{ seconds} \qquad \text{D-9}$$

This correction has been applied to obtain the detonation times given in Table 1.

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13. ABSTRACT

Two 10 ton charges composed of slurry type explosives designed to be detonated underwater were detonated on February 16 and 21 (GMT) 1968. The explosives were housed in a container specially designed by IIT Research Institute. Shot number 1 detonated at 1,825 feet and decended with a terminal velocity of 18.9 ft/sec. Shot number 2 detonated at 3,025 feet and decended with a terminal velocity of 18.8 ft/sec. The charges had a yield equivalent to 12 to 13 tons of TNT on an energy basis. The bubble pulse period for these charges was equivalent to 21 tons of TNT.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Slurry Explosive						
Underwater Detonation						
Underwater Terminal Velocity						
Bubble Pulse Period						
Shock Wave						
Energy						
Underwater Acoustic Telemetry						
Radio Telemetry						
Buoy						
Hydrophone						

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